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MODELLING ROAD SURFACE SEDIMENT PRODUCTION USING A VECTOR GEOGRAPHIC INFORMATION SYSTEM

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ABSTRACT

Field investigations indicate that unpaved roads are the largest sediment source on St John, US Virgin Islands. Cross-sectional measurements of eroded road surfaces were used to establish an empirical relationship to predict annual road surface erosion as a function of road gradient and contributing drainage area. A model (ROADMOD) for estimating and mapping average annual sediment production from a road network was developed by combining this empirical relationship with a series of network algorithms to analyse road data stored in a vector geographic information system.

ROADMOD was used to estimate road surface erosion in two St John catchments with very different road densities but similar land cover, topography and soils. Unpaved roads were found to increase sediment production in the more densely roaded catchment by a factor of three to eight, and in the less-roaded catchment by a factor of 1·3–2·0. Turbidity measurements in the receiving bays of these two catchments are consistent with model predictions and observed sediment delivery processes.

Although this model was developed specifically for St John, it can easily be adapted to other locations by substituting a locally derived predictive equation for road erosion. Model assumptions, limitations and potential improvements are discussed. © 1998 John Wiley & Sons, Ltd.

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INTRODUCTION

Accelerated sediment production and delivery are of concern on the island of St John in the eastern Caribbean because they threaten key resources at Virgin Islands National Park (VINP). VINP incorporates more than half of St John and 23 km^2 of its surrounding waters. White sand beaches, coral reefs and clear nearshore waters are the primary attractions of the Park, but corals are extremely sensitive to elevated levels of turbidity and suspended sediment (Rogers, 1990; Sebens, 1994). Local residents report elevated turbidity in many of the bays surrounding St John after even moderate storms. The source(s) of this elevated turbidity have never been clearly identified, but it is widely suspected that accelerated land development contributes to this problem.

Field investigations by the authors, together with Dr William Dietrich of the University of California at Berkeley, found little evidence of surface erosion or mass movements on most of St John (Anderson, 1994; MacDonald *et al*., 1997). Approximately 82 per cent of St John is covered by woodland, dry thicket or scrub, and secondary regrowth (Table I) (Woodbury and Weaver, 1987). There is virtually no agricultural or forest harvest activity on the island, and pastures occupy only 2 per cent of the land area. The soil surface is heavily armoured with large rocks (>50 mm intermediate diameter). The most obvious land disturbances are urban development, private home construction, and the road network established to service these uses. Sediment discharge from individual home construction sites, however, appears to be minimized by the limited extent of the disturbed areas and the widespread use of silt fences and vegetative filters to treat site runoff (Anderson, 1994).

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Table I. Land use and vegetation types on St John (from Woodbury and Weaver, 1987)

	Percentage of area
Dry evergreen woodland	33
Dry evergreen thicket/scrub	21
Moist evergreen forest	17
Secondary regrowth	11
Urban areas	2·6
Pasture	2
Mangroves, salt flats and lagoons	2·3
Other (thorn and cactus, rock pavement, etc.)	11·1
Total	100

In contrast, there are an estimated 56 km of unpaved roads on the 50 km^2 island, and these often exhibited deep surface rutting. Accumulations of fine sediment were evident where roads drained onto hillslopes or to downstream locations such as mangrove swamps and coastal salt ponds. These observations, together with our estimates of sediment yields from undisturbed watersheds (MacDonald *et al*., 1997), led us to posit that erosion from unpaved roads is the largest source of sediment on St John.

The primacy of unpaved roads as sediment sources in rural and forest lands has been documented by a number of studies (e.g. Haupt, 1959; Hafley, 1975; Ward, 1985). In steep humid environments, road-related landslides and debris flows often are the principal mechanism of sediment mobilization (Amaranthus *et al*., 1985; Coker and Fahey, 1993; Scatena, 1993). In the absence of mass failures, the primary source of sediment is surface erosion from the road surface, cut slopes, and sidecast and fill materials (e.g. Campbell and Stednick, 1983; Reid and Dunne, 1984; Bilby *et al*., 1989). The relative importance of these latter sources varies considerably between sites and with factors such as road use (Reid and Dunne, 1984; Swift, 1984; Coker *et al*., 1993).

On the basis of these studies and our field observations, our objectives were: (1) to measure road surface erosion at selected sites on St John; (2) to develop a procedure to estimate road surface erosion from all unpaved road segments; and (3) to develop a spatially explicit procedure for estimating sediment production and delivery from existing and anticipated road networks. These spatially distributed estimates of erosion and sediment production are necessary for quantitative assessments of sediment routing to downstream locations. Spatially explicit procedures are important because the various bays have different values, uses and flushing rates; this results in varying levels of sensitivity and public concern with regard to fine sediment inputs. Quantification of sediment inputs at various locations is also necessary to evaluate the relative impact of different scenarios and to maximize the effectiveness of mitigation efforts.

This paper presents our field observations and the resultant model (ROADMOD) that integrates road data with a vector geographic information system (GIS) to predict the amount of sediment produced by unpaved road networks on St John. Predicted road erosion from two catchments is compared to natural erosion rates and measured turbidities offshore.

The specific empirical relationships in ROADMOD mean that the model predictions are valid only for St John. However, comparable field data could easily be collected for other areas and substituted into ROADMOD, allowing the model to be readily adapted to other locations.

FIELD OBSERVATIONS AND EROSION CONSIDERATIONS

Many variables potentially affect the rate of road surface erosion. These include: road gradient (e.g. Burroughs and King, 1989); amount, timing and type of road use (e.g. Reid and Dunne, 1984; Coker *et al*., 1993); distance between drainage points (e.g. Packer, 1967); physical characteristics of the road surface (e.g. Burroughs and King, 1985); rainfall amounts and intensities (e.g. Megahan *et al*., 1991); position on the slope (Packer, 1967); gradient and aspect of the slope across which a road is built (e.g. Packer, 1967); and microtopography of the road surface (Campbell and Stednick, 1983). Although we were not able to investigate all of these factors, theoretical considerations and our field observations suggested that contributing road drainage area and road gradient were

of primary importance. These two factors incorporate, or are surrogates for, the critical variables in calculating boundary shear stress and sediment transport capacity. The product of contributing area and slope has been extensively used in surface erosion models (e.g. Moore and Wilson, 1992; Dietrich *et al*., 1993), and contributing road drainage area and gradient offer the advantage of being easily measured in the field. In addition, these two factors vary greatly on St John relative to most of the other factors which might influence road erosion rates.

Road use is believed to be a relatively unimportant erosion factor on St John because most unpaved roads are built to access a very small number of private homes, many of which are only used during the drier winter season. Traffic on unpaved surfaces therefore consists almost exclusively of jeeps and other light vehicles which have a much smaller effect on road erosion rates than heavier commercial vehicles (e.g. Reid and Dunne, 1984). Primary roads with higher traffic loads are generally paved.

Unpaved roads on St John are typically regraded with native, easily accessed soil materials rather than gravel. Soils are relatively consistent (SCS, 1970), which implies little variation in the erodibility of regraded surfaces. Our observations indicated that the road surfaces were extremely erodible, with substantial amounts of sediment being mobilized during even mild storm events. The widespread use of local materials results in road surfaces that become rapidly rilled and incised. The concentration of surface runoff in wheel ruts quickly negates design effects such as outsloping.

We saw little evidence for surface runoff onto road surfaces from adjacent hillslopes. ROADMOD and our field measurements therefore incorporated drainage area estimates only from roads (paved and unpaved) and adjacent impermeable surfaces. On steeper sideslopes we occasionally observed small slumps from the cut banks. However, our field observations and a careful inspection of old aerial photos revealed only one case in which road construction and drainage on St John had caused a landslide or debris flow similar to those observed in more humid areas such as New Zealand (Coker and Fahey, 1993), the US Pacific Northwest (Reid *et al*., 1981), and the wetter part of Puerto Rico (Scatena, 1993).

FIELD METHODS AND RESULTS

For the reasons discussed above, we focused our measurements on the amount of surface material removed from the road surface. Our field observations of road improvement practices on St John confirmed that road construction and grading produced a planar road surface. Thus the amount of eroded material could be determined by placing a straight edge across the incised road surface and measuring the cross-sectional area of material that had been removed. Although some of the ‘missing’ material may have simply been compacted, the ruts typically were eroded to a base level controlled by the presence of cobbles or bedrock. The narrowness of the roads and the propensity of people to drive on the less-rutted road edges also means compaction rates are not likely to differ substantially across the road except for a few months immediately after grading. Use of a conservative estimate for the density of the eroded material ($1{\cdot}5\,\mathrm{Mg\,m^{-3}}$) also helped compensate for possible compaction. Measurements were made at 23 widely distributed locations throughout the Fish Bay catchment, and were chosen to represent a wide range of gradients (4–37 per cent) and contributing areas (45–$970\,\mathrm{m^2}$) (Table II). These were selectively made at locations where the road surface, rather than a road ditch, conveyed most of the road runoff.

Road networks were mapped in the field on enlarged topographic maps. Our basic mapping unit was the road segment, which was defined as a continuous road surface that began and ended at an intersection with another road, a change in road characteristics (e.g. change in gradient), or a point at which surface runoff was channelled to a culvert or other point of discharge. The length and width of each road segment was measured by tape or pacing, and a Brunton clinometer was used to estimate the mean road gradient for each segment. All culverts and other drainage points were recorded. In cases where some but not all of the flow was diverted (for example, at many road intersections), the proportion of flow routed in each direction was estimated by evaluating the surface topography, drainage pattern, and deposition of sediment. The road surface (paved or unpaved) was also recorded for each segment. The age of the road or time since last grading was determined from permit signs and querying local residents; these periods generally ranged from one to three years. Road use was qualitatively estimated as low, medium or high based on the number of homes serviced by the road.

Table II. Characteristics of 23 measured road cross-sections, Fish Bay catchment

Site ID	Drainage area (m^2)	Slope (%)	Slope×Area	Estimated erosion ($m^3 m^{-1}$)	Age (years)	Estimated erosion rate ($m^3 m^{-1} a^{-1}$)
1C	156	23	35·9	0·020	1	0·020
1D	700	26	182·0	0·088	1	0·088
1E	970	21	203·7	0·200	1	0·200
1G	225	16	36·0	0·030	1	0·030
1H	715	19	135·9	0·180	1	0·180
1K	540	9	48·6	0·075	1	0·075
1L	140	20	28·0	0·021	1	0·021
1M	460	16	73·6	0·075	1	0·075
2C	180	17	30·6	0·060	1	0·060
2D	537	12	64·4	0·092	1	0·092
2E	950	16	152·0	0·100	1	0·100
2K	560	19	106·4	0·060	1	0·060
3A	255	19	48·5	0·120	2	0·060
3B	45	8	3·6	0·047	2	0·024
3C	95	26	24·7	0·160	2	0·080
4G	160	13	20·8	0·250	3	0·083
5E	84	19	16·0	0·140	3	0·047
7K	330	18	59·4	0·200	3	0·067
7L	540	11	59·4	0·140	3	0·047
8H	180	37	66·6	0·290	3	0·097
8P	287	25	71·8	0·200	3	0·067
12C	210	4	8·4	0·240	4	0·060
15H	448	23	103·0	0·157	3	0·052

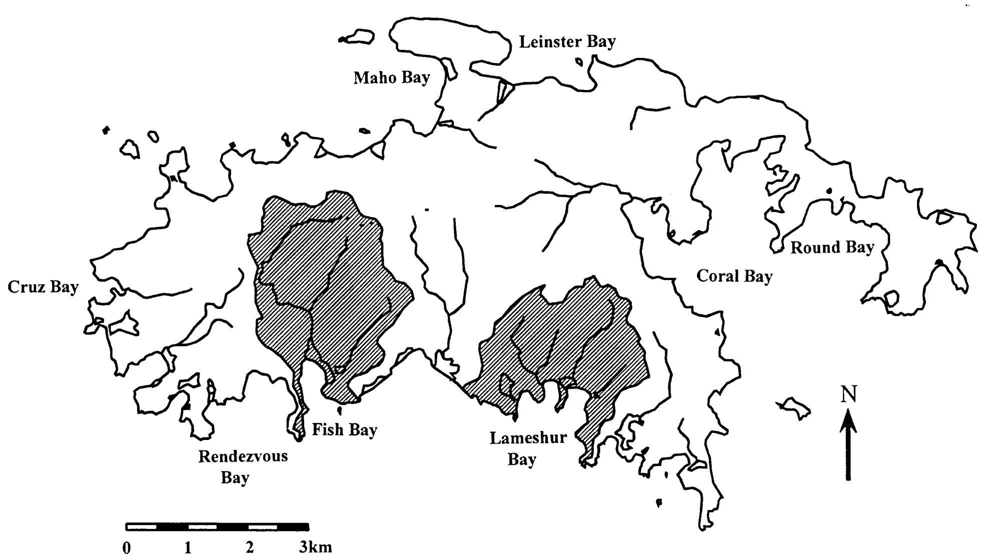

Figure 1. Map of St John with the Fish Bay and Lameshur Bay catchments

Table III. Characteristics of 185 road segments measured in the Fish Bay catchment, St John, January 1994

	Mean	Minimum	Maximum	St dev.
Length (m)	84	10	518	79
Width (m)	3·8	2·0	6·5	1·6
Slope (%)	8·0	0	37	7·3

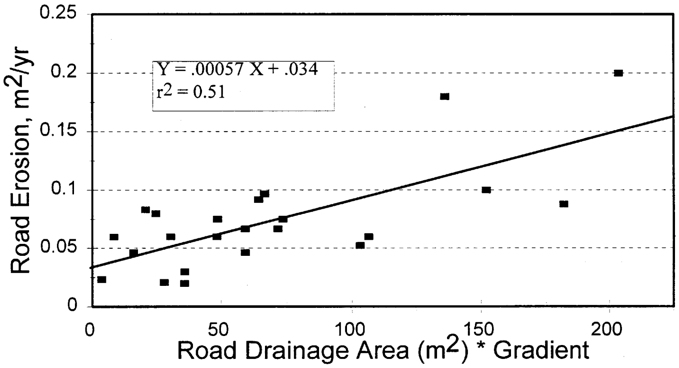

Figure 2. Road erosion vs. the product of road surface drainage area and road gradient, divided by the time since construction or last grading in years, Fish Bay catchment, St John

Our field work focused on the Fish Bay catchment (Figure 1) because of its rapidly expanding network of roads. We mapped 185 road segments and 15·4 km of roads in this 6·1 km^2 catchment (Table III). Only 46 per cent of the roads were paved. Stepwise regression found that the measured erosion rate was best related to the product of road gradient and the road surface area draining to that point, divided by the time since construction or last grading in years (Figure 2). Since our data indicated that the erosion rate was linear with time, the resulting predictive equation was:

$$E = 0{\cdot}0057\,AS + 0{\cdot}034\,\mathrm{m^3\,m^{-1}\,a^{-1}} \tag{1}$$

where E is the estimated cross-sectional road erosion (in $\mathrm{m^3\,m^{-1}\,a^{-1}}$), A is the upslope road drainage area (in $\mathrm{m^2}$), and S is the road gradient (in m/m). This equation explained 51 per cent of the variance in road surface erosion and had a standard error of $0{\cdot}031\,\mathrm{m^3\,m^{-1}\,a^{-1}}$.

By expressing road surface erosion in cubic metres of material removed per metre of road length per year, annual erosion for a homogeneous segment can be calculated by multiplying this value by the segment length. The prediction equation was not significantly improved by adding a factor for estimated road use nor by expressing erosion rates as a function of road width.

A more accurate predictive equation might be expected with additional or more precise data on factors such as the amount and timing of rainfall, total surface runoff, road use, and road surface characteristics. Direct measurements of road runoff and sediment concentrations would be preferable to measured changes in the road cross-section, but the former are much more difficult to obtain because of the sporadic nature of rainfall on St John (most rainfall comes in short showers that generate little runoff) and relatively dry conditions (monthly potential evapotranspiration normally exceeds precipitation for nine months of the year; Figure 3). Our limited field time on St John also precluded us from collecting more detailed data from the measured road segments or data from more than a few sites outside the Fish Bay catchment. Nevertheless, our success in accounting for slightly more than half of the measured variability in road surface erosion with just three independent variables (contributing area, slope and time) led us to develop a model which provides the first estimates of sediment production and delivery from unpaved roads on St John.

SEDIMENT DELIVERY

The routing of sediment into and through the stream network is a critical but difficult issue (e.g. Walling, 1983). In the case of road erosion on St John, estimates of sediment delivery were facilitated by the fine texture of the eroded sediment, the relative absence of overland flow on vegetated hillslopes, the periodic occurrence of relatively large stormflows, and the fact that stream channels on St John are generally confined, short and steep.

Pebble counts and our field observations indicated that the beds of the major channels were a mixture of bedrock, boulders and cobbles (Anderson, 1994). Finer bed materials were observed in some of the lower-

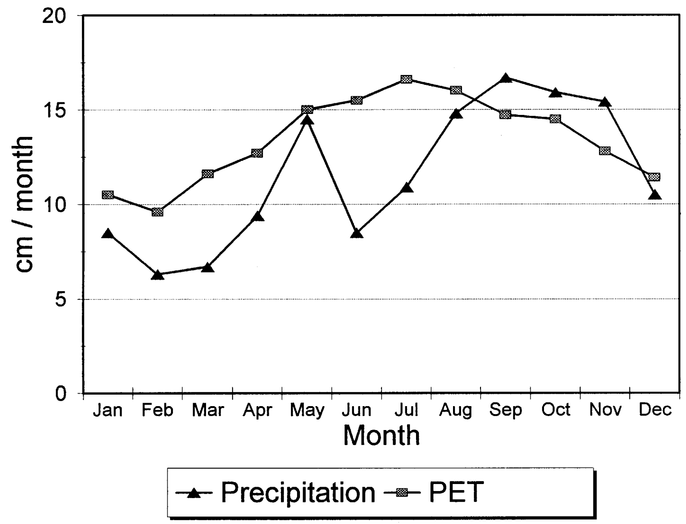

Figure 3. Average precipitation and estimated potential evapotranspiration (PET), Cruz Bay, St John (from Mount, 1993)

gradient headwater reaches subject to large sediment inputs from unpaved roads and a commercial rock-crushing operation. Finer bed materials also were observed in lower-gradient reaches immediately upstream of coastal bays and ponds. However, sediment storage locations were largely filled in both sets of channels, and this suggests that any continuing inputs of fine sediment are simply routed through the channel network. Similarly, potential sediment storage in the remaining reaches is limited by the narrow valley bottoms and the lack of interstitial spaces below the armoured surface layer (Anderson, 1994). Precipitation data, geomorphic evidence, and the limited discharge record all indicate that hurricanes and other tropical storms generate flows of 1–5 $cm\,h^{-1}$ (30–140 $l\,s^{-1}\,ha^{-1}$) (Anderson, 1994). Standard formulas for predicting sediment mobilization (e.g. Simons and Senturk, 1992) confirm that the fine sediment characteristic of road surface erosion (i.e. sands, silts and clays) can easily be transported in both the tributary and mainstem channels.

This logic led us to assume that 100 per cent of the sediment routed to the stream channels by roadside ditches and culverts was delivered to the bays. We assumed that road runoff directed onto unchannelled vegetated hillslopes had a sediment delivery ratio of zero, which is consistent with studies in temperate forested areas (e.g. Campbell and Stednick, 1983; Burroughs and King, 1989). In the absence of any other information, a sediment delivery ratio of 0·5 was assumed for road segments that discharged onto unvegetated hillslopes or directly into mangrove swamps. While there is considerable uncertainty associated with the latter value (e.g. Wolanski, 1995), our estimated sediment delivery rates were relatively insensitive to this estimated ratio because so few locations discharged to these sites (Anderson, 1994).

SPATIAL MODELLING OF ROAD SEDIMENT PRODUCTION

Equation 1 can easily be applied to an individual road segment if the road dimensions and average gradient are both known. However, estimating road surface erosion from an extensive network of paved and unpaved roads with varying gradients, dimensions and multiple points of runoff is a far more complex undertaking. To address these difficulties, we developed a procedure to automate the application of Equation 1 to digitized road network data.

The program written in C for this purpose (ROADMOD) operates on a network of road segments digitized in an arc-node vector GIS format. The program requires that each road segment be represented as a vector (arc) possessing direction, length and connectivity with adjacent road segments or drainage points. Each arc begins at a specified *x,y* coordinate (origin node) and ends at another *x,y* coordinate (destination node). The integer indexing one segment's destination node must be unique and identical to that of the next segment's origin node if runoff from the first segment flows on to the second.

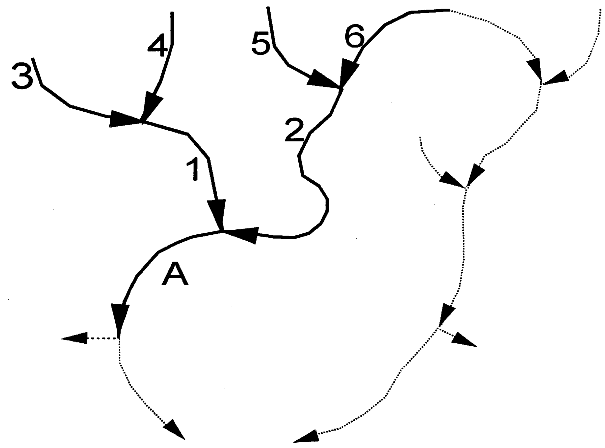

Figure 4. Road erosion prediction by ROADMOD. The rate of erosion for segment A is predicted from the road surface area of runoff-contributing segments 1 to 6 and the area, length and slope of segment A

ROADMOD operates on an ASCII output file generated by Arc/Info, a widely used vector-based commercial GIS software package. Before executing ROADMOD, the following attributes must be assigned to each digitized road segment:

(1) unique segment identification number;
(2) origin node identification number;
(3) destination node identification number;
(4) road length in metres;
(5) average road width in metres;
(6) average road gradient in per cent;
(7) road type (paved, unpaved or culvert/discharge point);
(8) runoff factor estimating the proportion of flow from the adjacent uphill segment that continues onto the subject road segment (this allows flow to be split into multiple directions).

ROADMOD estimates annual sediment production from the road network in the following manner. First, ROADMOD reads and internally stores the attribute data for each road segment. The model takes the first road segment in the database and identifies all road segments uphill of and connected to that segment (Figure 4). By evaluating the width and length of each uphill road segment, and by compensating for the proportion of runoff diverted before reaching the examined segment, ROADMOD calculates an effective road drainage area at the midpoint of the subject segment. If the subject segment is paved, the predicted erosion is zero. If the segment is not paved, this effective drainage area, together with the average slope of the segment, is inserted into Equation 1 to predict the cross-sectional road surface erosion (in $m^3 m^{-1} a^{-1}$) for the middle of the segment. This value is then multiplied by the road length to estimate the average annual erosion from that segment. ROADMOD repeats this analysis for each road segment in the database.

After estimating the annual sediment production from each road segment, ROADMOD loops through the road data a second time to identify every outlet segment in the network (Figure 5). An outlet segment is defined as any road, culvert or point of discharge that does not connect to a downhill counterpart and therefore discharges sediment to a hillslope, stream channel or coastal outlet. An implicit assumption of this step is that all sediment eroded from a road surface is transported to a downstream road or outlet segment.

ROADMOD then sums the sediment delivered to each outlet from all contributing roads. The algorithm for this second data processing loop is similar to that used to estimate the sediment produced from each road segment, except that the program maintains a running account of contributed sediment from upslope roads rather than contributing drainage area.

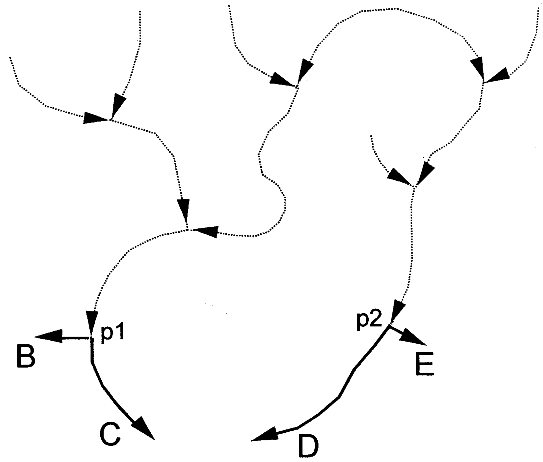

Figure 5. Sediment discharge prediction by ROADMOD. The network analysis algorithm identifies segments B, C, D and E as outlets from the road network. Average annual sediment delivery from the end of each outlet segment is estimated by summing the erosion from all contributing segments and accounting for the distribution of runoff at points of divergence (e.g. points *p1* and *p2*)

A digital copy of the ROADMOD source code and a brief user's guide can be obtained by sending a DOS-formatted diskette to the senior author.

MODEL ASSUMPTIONS AND APPLICABILITY

As with any model, a number of simplifying assumptions have been made in order to mathematically represent the system and produce a useable model. The key assumptions underlying ROADMOD are discussed below.

Assumption 1: The bulk of road runoff is conveyed by the road surface. Our field measurements of road surface erosion were biased in that they usually were located where the road surface, rather than a road ditch, conveyed the bulk of storm runoff. If road ditches are conveying most off the runoff, ROADMOD probably will overestimate road surface erosion.

Assumption 2: Sediment storage in the road network is negligible. ROADMOD assumes that all sediment eroded from the road surface is conveyed through successive segments until it reaches an outlet. This assumption of negligible storage within a road segment is consistent with our field observations.

Assumption 3: Cutbank, ditch and sidecast erosion is negligible. This model estimates sediment production from unpaved road surfaces only. In cases where cutbanks, ditches and fill slopes are also eroding, the model underestimates sediment production.

Assumption 4: Average road slopes and widths are reasonable modelling approximations for the entire road segment. ROADMOD treats each road segment as a homogeneous entity having a constant width and slope. In reality no road segment is perfectly homogeneous. This is not a serious modelling problem, however, since a heterogeneous road segment can easily be represented as a series of shorter, more homogeneous segments. Also, the linearity in Equation 1 means that the inaccuracies due to lumping road segments will tend to average out.

Assumption 5: Both effective drainage area and sediment routing can be approximated with a single flow routing factor. ROADMOD allows runoff to be split in multiple directions using a runoff factor for each road segment. A runoff factor of 1·0 indicates that the subject segment receives 100 per cent of the runoff from an upslope segment, while a factor of zero indicates that all the runoff is diverted to either another road or an outlet segment such as a culvert. This runoff factor is used to adjust both the upslope drainage area and the routing of sediment through the road network. Use of a single factor appears reasonable since the detached sediment is transported by the road surface runoff. Of greater concern is the uncertainty in estimating the magnitude of this factor, particularly when the proportion of runoff flowing in different directions may change over time with road grading or the progressive development of ruts and rills.

Assumption 6: Climate conditions during the period modelled will be similar to the conditions prevailing in 1990–1993. Equation 1 is based on data collected from roads constructed or regraded between 1990 and 1993. Annual precipitation over these four years ranged from 74 to 96 per cent of the 38 year average, and there were few major storms (Anderson, 1994). Thus the measured road erosion values are probably low relative to an average year and ROADMOD is underpredicting sediment production.

Other considerations in the use of ROADMOD include the consistency of road surface erosion rates over space and time. ROADMOD is strictly applicable only to the Fish Bay catchment where road surface erosion measurements were made. This relationship was applied to unpaved roads in other catchments on St John because there were no obvious differences in soils or road surface characteristics.

Also, road surface erosion rates are calculated as annual average rates and are presumed to be linear with time. Measured road surface erosion rates, however, were higher at four other sites where the roads were known to have been constructed or regraded within the previous four to eight months. The limited data and lack of a consistent relationship for these new or recently regraded roads prevented us from incorporating a time-dependent variable to account for the initially much higher rate of erosion suggested by these observations and other studies (e.g. King, 1984). Incorporation of a time-dependent variable for new or recently regraded roads would both improve and further increase predicted erosion rates. On the other hand, the assumption of linearity with time in Equation 1 is probably realistic on a 1–3 year time scale, as the observed erosion rates are so high that unpaved roads are typically regraded at intervals of eight months to three years in order to remain passable.

It is also of interest that Equation 1 has a small but positive *y*-intercept. Although the data should go through the origin and might be expected to follow a parabolic function, our results from road segments with small slope-contributing area products did not show these expected patterns.

APPLICATION OF ROADMOD TO TWO CATCHMENTS ON ST JOHN

ROADMOD was applied to road data gathered in two St John catchments, Fish Bay and Lameshur Bay (Figure 1). These basins were chosen because of their differences in road density and land development, and because they were the subject of a parallel discharge and sediment yield study that has since been abandoned (Gellis, undated). The $6{\cdot}1\,km^2$ Fish Bay basin has been subject to extensive home building and associated road construction. The $4{\cdot}4\,km^2$ Lameshur Bay basin remains relatively undisturbed with few roads and virtually no residential, commercial or industrial development.

Both the Fish Bay and Lameshur catchments are covered primarily by forest, thicket and scrub vegetation (Woodbury and Weaver, 1987). Gravelly and stony clay loam soils occupy 88 and 86 per cent of the Fish Bay and Lameshur Bay catchments, respectively (SCS, 1970). Both catchments are generally steep, with slopes in excess of 20 per cent characterizing 69 per cent of the Fish Bay basin and 83 per cent of the Lameshur Bay basin.

All the roads in each catchment were mapped in the field. Road lengths, widths and gradient were recorded for each segment. Road surface characteristics, connectivity and downhill directions were also noted, along with the location of culverts and other drainage points. These road segments and culverts were later digitized as a network of vectors, and the eight attributes required by ROADMOD were assigned to each segment.

Figures 6 and 7 show the road network and predicted sediment delivery at each outlet segment for the lower and upper parts of the Fish Bay catchment, respectively. The total predicted road surface erosion for this catchment is $390\,m^3$ per year. In contrast, the limited road network in the Lameshur Bay catchment is estimated to generate only about $65\,m^3$ of sediment per year. Our field assessment of sediment delivery pathways indicates that approximately 70 and 50 per cent of road-derived sediment reaches the marine zone each year from the Fish Bay and Lameshur Bay catchments, respectively. Thus the total road-related sediment delivered to Fish Bay and its adjoining mangroves is nearly an order of magnitude greater than for Lameshur Bay ($270\,m^3\,a^{-1}$ vs. $30\,m^3\,a^{-1}$).

While a long-term, intensive monitoring programme would be necessary to verify these estimates, these results are consistent with measured turbidities in Fish and Lameshur Bays. From 1988 to 1993 the median monthly turbidity at three sites in Lameshur Bay was 0·34 nephelometric turbidity units (NTUs), while the median monthly value at Fish Bay was 1·05 NTUs (NPS, 1995). A non-parametric Wilcoxon rank sum test

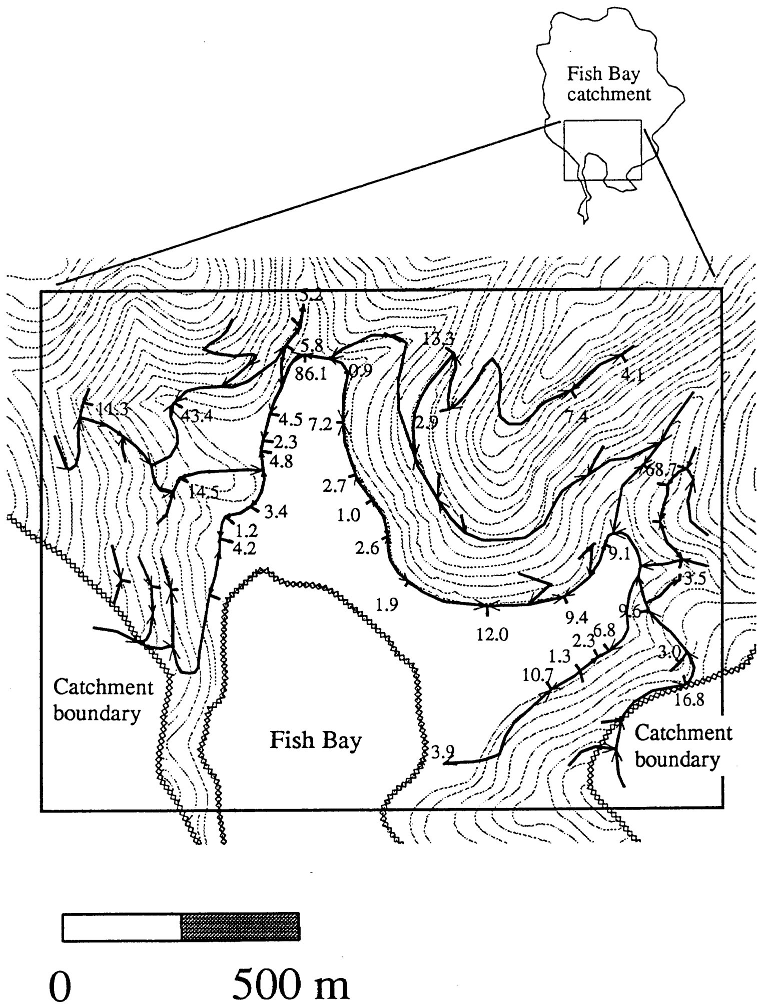

Figure 6. Predicted road sediment delivery from culverts and other road runoff outlets in the lower Fish Bay catchment, in cubic metres per year. Solid lines denote roads, stippled lines denote 40-foot hypsometric contours. Roads in the lower left part of the map are paved and have no sediment delivery values

indicates that the difference in means between Fish Bay and each of the Lameshur Bay locations is significant at $p<0{\cdot}001$.

Since both catchments are on the south side of the island and have similar soils, climate, vegetation and topography, we posit that these differences in turbidity are due primarily to land use differences. More specifically, the results from ROADMOD, together with the relative absence of observed sediment from other land use activities, lead us to believe that road-related erosion is the primary cause of the measured differences in turbidity. The turbidity data also suggest that the ROADMOD-derived predictions are a reasonable index of road-related erosion, and accurate on a relative basis. Since some sediment is also derived from cut banks, drainage ditches and sidecast materials, actual erosion rates and sediment yields could be substantially higher than the values calculated using ROADMOD.

These estimated sediment yields from road surface erosion can be contrasted with the estimated average annual sediment yield under natural conditions of 7–30 $m^3 km^{-2} a^{-1}$ (Anderson, 1994). This natural sediment yield is low compared to many tropical environments, but it is consistent with the well-armoured soil surface, the near-absence of landslides, and the intermittent nature of runoff events on St John. Even if one assumes a conservative density of 1·5 $Mg\,m^{-3}$ for the material eroded from the road surfaces, road erosion is estimated to have increased sediment delivery to Fish Bay by three to eight times and to Lameshur Bay by 1·3–2·0 times.

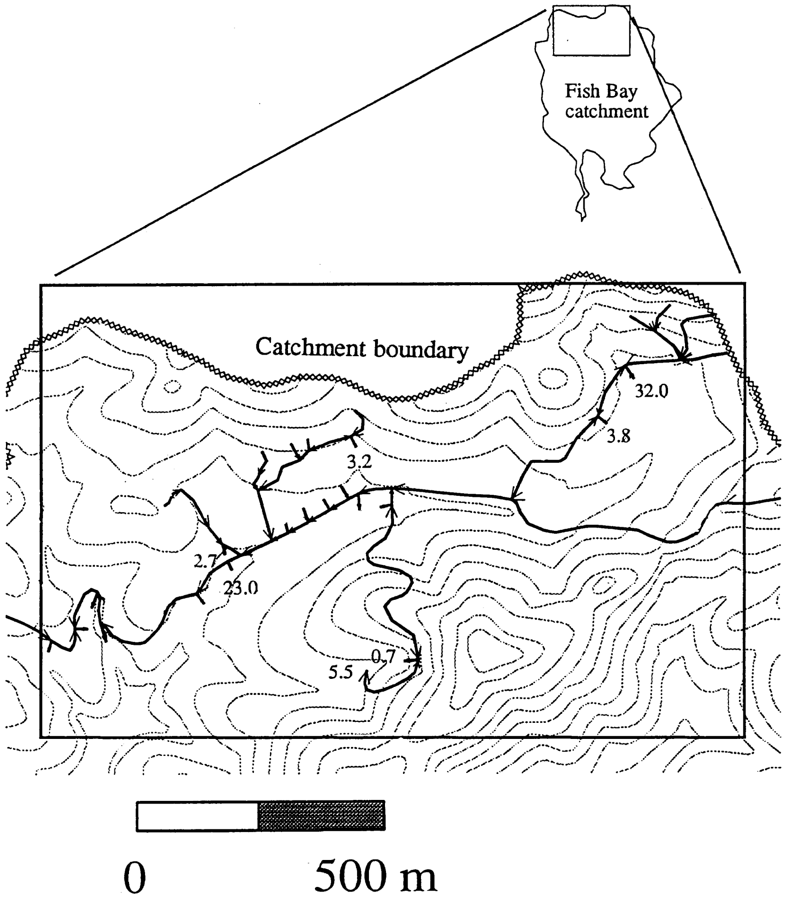

Figure 7. Predicted road sediment delivery from culverts and other road runoff outlets in the upper Fish Bay catchment, in cubic metres per year. Solid lines denote roads, stippled lines denote 40-foot hypsometric contours. The main east–west road is paved, but some of the outlet segments from this road have high predicted sediment yields due to the sediment inputs from unpaved driveways and spur roads

These large increases are insensitive to most of the basic assumptions of ROADMOD. For example, if the sediment delivery ratio for unvegetated hillslopes and mangrove swamps is assumed to be 0·0 instead of 0·5, this reduces the estimated road-related sediment yields to Fish Bay and Lameshur Bay by only 8 and 26 per cent, respectively. The amount of road-derived sediment will also be linearly reduced if one assumed differential compaction between the eroded areas. However, it is difficult to justify a more than 20–30 per cent difference in dry bulk density, and the dry bulk density of a newly constructed or graded road surface is probably closer to $2\,Mg\,m^{-3}$ than our assumed value of $1{\cdot}5\,Mg\,m^{-3}$. Perhaps the most critical assumption is the sediment delivery ratio of 1·0 for transporting sediment down segments and through the channel network. Given the channel characteristics and observed discharge regime, we are relatively confident that the fine sediment is indeed transported through the stream network. Sediment storage within the road network is much more difficult to evaluate, but as long as road runoff is confined to well-defined rills and ditches, the opportunities for long-term storage are extremely limited.

Given the sensitivity of coral reefs and other public resources to fine sediment, these increases in sediment delivery clearly warrant the attention of resource managers and land use planners in the Virgin Islands. Additional studies could assist in: (1) quantifying other road-related erosion processes; (2) better quantifying the relationship between erosion rate and age of the road surface; (3) better assessing the delivery of road-derived sediment; (4) evaluating road surface erosion at other sites on St John; (5) assessing the impact of

vehicle traffic on road erosion rates; and (6) determining erosion rates as a function of individual storm events. Such data may lead to a second-generation road erosion and sediment delivery model which will provide more precise estimates of road-related erosion. However, even at its current stage of development, ROADMOD's spatially distributed estimates of road erosion provide valuable insights into the relative sediment impact of present and future roads on St John.

CONCLUSIONS

Unpaved roads appear to be the primary source of fine sediment on St John. The average annual rate of erosion from unpaved road surfaces is approximately proportional to the product of the road gradient and contributing road drainage area. ROADMOD provides an automated procedure for estimating sediment production from a digital vector representation of a road network. The spatially distributed results can provide important guidance to resource managers and land use planners concerned with sediment impacts. ROADMOD's GIS-based approach may be particularly useful where road data are already digitized.

ROADMOD can be easily adapted to other locations by substituting a locally derived road erosion prediction equation. Possible improvements to ROADMOD include: (1) incorporating estimates of erosion from road cuts, fill slopes and drainage ditches; (2) incorporating a time dependent erosion variable; (3) calibrating the model to individual runoff events so that varying weather conditions can be simulated; and (4) integrating the road sediment production model with a complementary hillslope and stream channel sediment delivery model.

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